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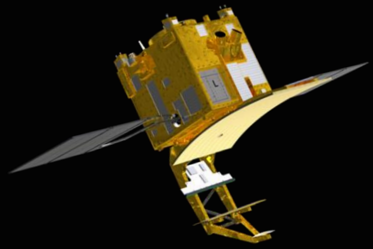

A Multi-frequency Wide-swath Spaceborne Cloud and Precipitation Imaging Radar

96th AMS Annual Meeting

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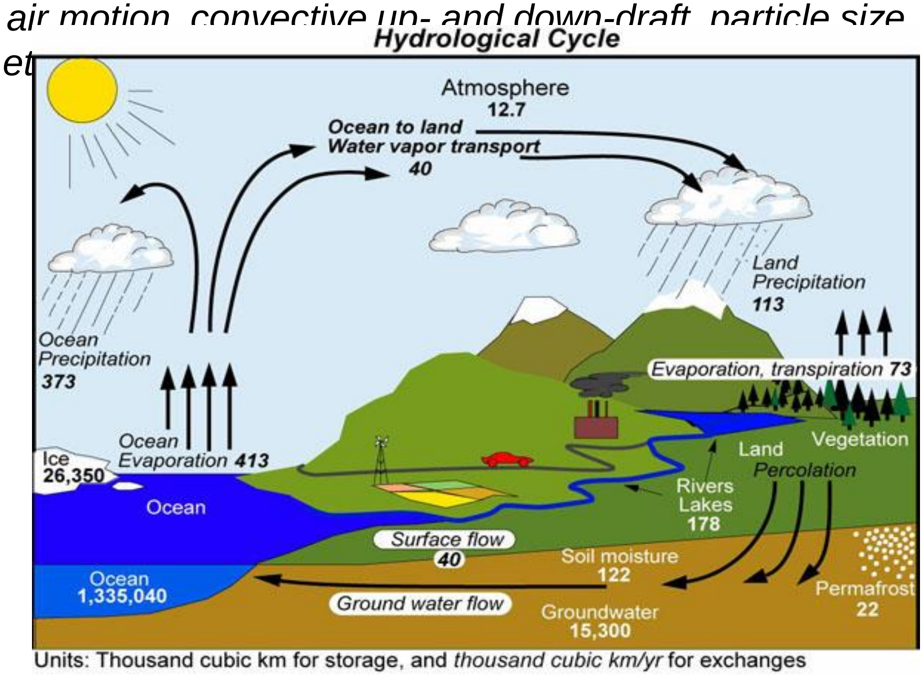
NASA Goddard Space Flight Center (GSFC):
Lihua Li, Paul Racette, Gerry Heymsfield, Matthew McLinden, Vijay Venkatesh, Michael Coon, Martin Perrine
Northrop Grumman Electronic Systems (NGES):
Richard Park, Michael Cooley, Pete Stenger, Thomas Spence, Tom Retelny

Outline

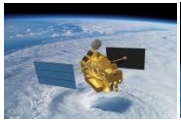
- Science Motivations
  - ➢ Science background
  - ➢ Spaceborne atmospheric radar past, current and future
- Cloud and Precipitation Radar Design Trade
  - ➢ Design trades
  - ➢ Performance parameters
- Technology development at GSFC and NGES
  - ➢ ACE Ka/W-band dual-frequency radar concept
  - ➢ CaPPM Ku/Ka/W-band tri-frequency radar concept
  - ➢ Dual or tri-frequency shared aperture antenna study
  - ➢ Ka-band AESA development
  - ➢ Radar digital receiver and processor
- Summary and Path Forward

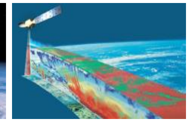
Science Motivations

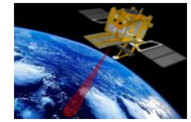
- Clouds and precipitation are among the greatest sources of uncertainty in climate change prediction. Global-scale measurements are critically needed.
- Multi-frequency radar with Doppler and imaging capability is crucial for improved understanding of the characteristics of clouds, precipitation, and their interaction.
  - *Provide quantitative estimates of Ice Water Path (IWP), Liquid Water Path (LWP), particle size, and particle phase with much higher accuracy than single frequency radar measurements.*
  - *Doppler velocity provides information on vertical air motion, convective up- and down-draft, particle size and classification, and latent heat transportation et*
- Decadal Survey (DS) Aerosol Cloud Ecosystem (**ACE**) calls for a dual frequency (Ka/W-band) radar.
- After the successful launch of GPM in 2014, a tri-frequency imaging Doppler radar concept as a CloudSat and GPM follow-on mission, Cloud and Precipitation Process Mission (**CaPPM**), is under development.



Spaceborne Atmospheric Radar
Past, Current and Future








	TRMM	CloudSat	EarthCare	GPM		ACE (GSFC/NGES)		CaPPM (GSFC/NGES)		
Frequency (GHz)	13.8	94	94	13.6	35.6	35	94	13.6	35	94
Primary Target	Rain	Clouds	Clouds	Rain/Snow		Clouds		Clouds & precipitation		
Measurements	Reflectivity	Reflectivity	Reflectivity, Doppler	Reflectivity		Reflectivity, Doppler		Reflectivity, Doppler, & Polarimetric (option)		
Retrieval Products	Rain rate	IWC, LWC	IWC,LWC	Rain rate, particle size		IWC, LWC, particle size		IWC,LWC, particle size, rain rate, weather system dynamics		
Orbit Altitude (km)	402	720	400	407		420		420		
Transmitter	SSPA Array	EIK	EIK	SSPA Array	SSPA Array	AESA	EIK	AESA	AESA	EIK or AESA
Tx Peak Power (W)	500	1820	1800	1012	146	2000	1600	2000	2000	1600
Antenna Size (m)	2.1	1.85	2.5	2.1	0.8	2.3x3.0 to 3.0x5.0		2.3x3.0 to 3.0x5.0		
Vertical Res. (m)	250	500	500	250	250/500	250	250	250		
Horizontal Res. (km)	5.2	1.4	0.8	5.2	5.2	2.0x1.5	0.75x1.0	5.0x4.0	2.0x1.5	0.75x1.0
Cross Track Swath (km)	245	Nadir	Nadir	245	120	120	Nadir	245	120	TBD
Nadir Sensitivity (dBZ)	18	-28	-35	17	12	-14.0	-34.0	1.0	-14.0	-34
Swath Sensitivity (dBZ)	18	N/A	N/A	17	12	-11.0	N/A	4.0	-11.0	TBD
Doppler Capability	No	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes
Polarimetric Capability	No	No	No	No	No	LDR	Optional	LDR	LDR	LDR

System Design and Associated Trades Are Closely Tied to Science Objectives

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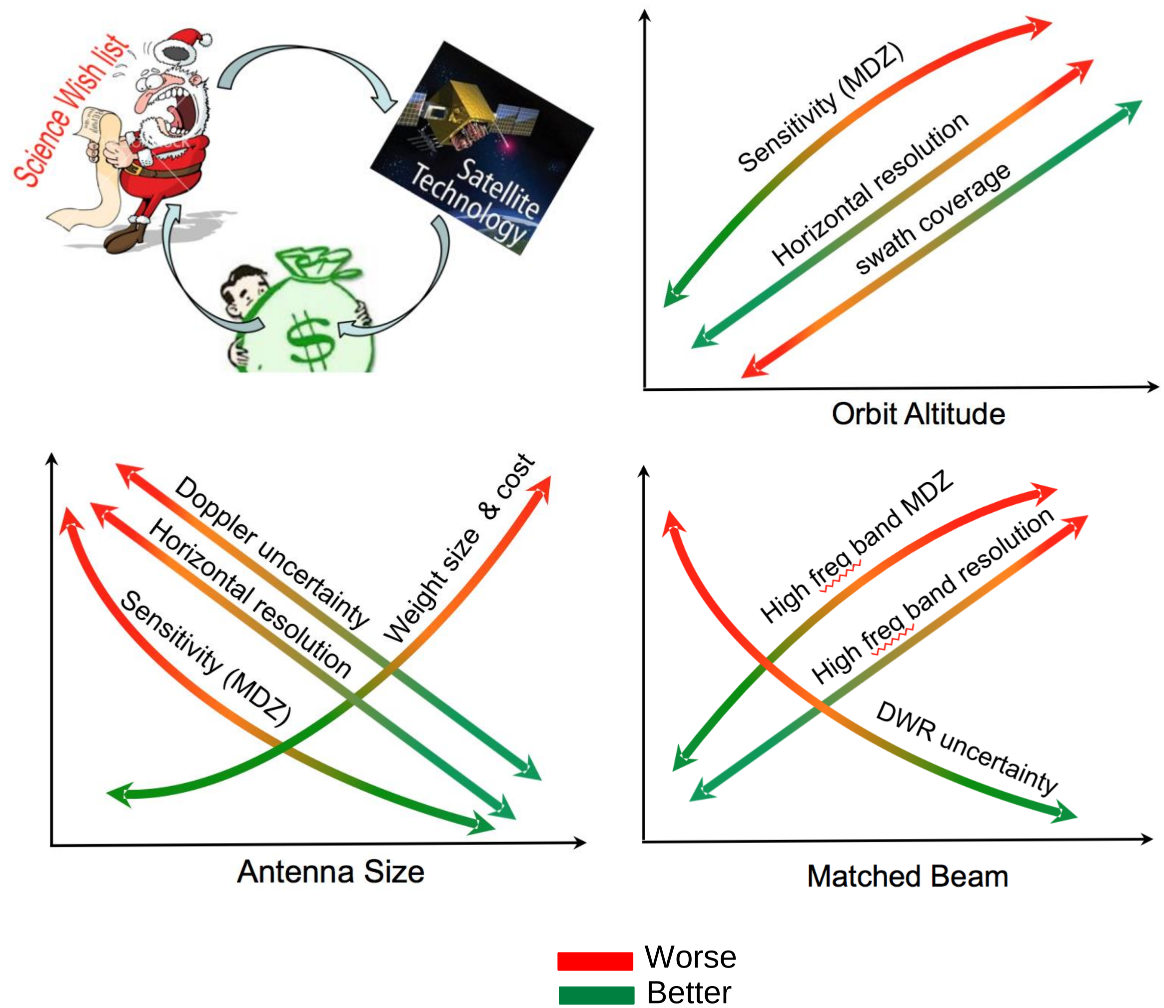
Science Requirements and Priorities Including,

- Orbit altitude
- Radar sensitivity
- Spatial resolution
- Range resolution
- Swath width
- Matched beam
- Doppler accuracy
- Polarimeteric operation

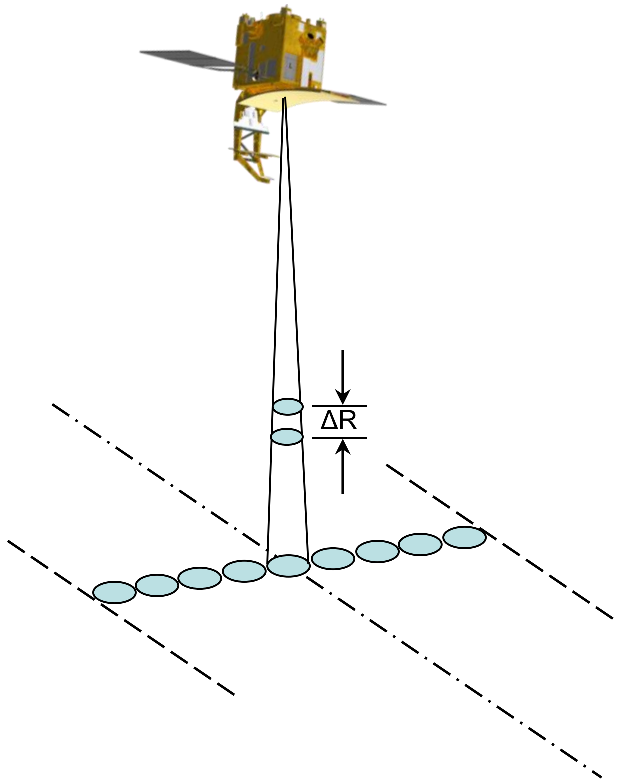
Radar Design Constraints

- Antenna size
- Primary power consumption
- Weight
- Data rate
- ...



What Can We Do With Current and Near Future Technologies

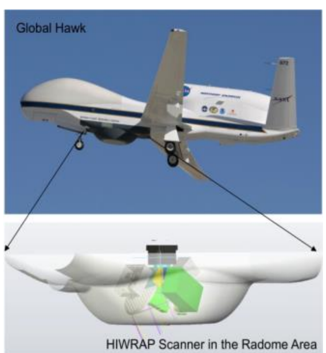
- Active Electrically Scanned Array (AESA) for Different Scanning Modes
  - AESA feeds enable programmable scanning modes and footprint size.
  - Matched beam for nonhomogeneous and high dynamic targets, or non matched beams for better sensitivity for homogeneous targets.
  - Wider swath with lower sensitivity for precipitation, or narrow swath with higher sensitivity for clouds.
  - Longer dwell time at angles of interest for better sensitivity
- Programmable Waveform and Digital Receiver for Different Tx/Rx Pulse Sequence
  - Shorter pulse for better range resolution or longer pulse for better sensitivity
  - Frequency diversity pulses for more independent samples or Doppler measurements
- Pulse Compression for Better Sensitivity
- Radiometric Channels



Advanced Radar Technology Development at NASA GSFC and NGES

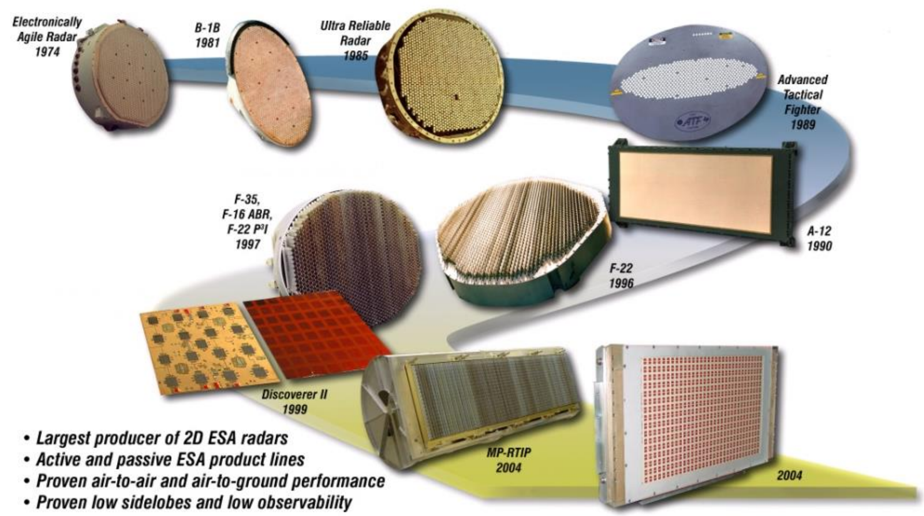
NASA GSFC

- TRMM and GPM science
- High altitude airborne radars cover frequencies from X, Ku, Ka to W-band
- NASA ESTO IIP2010 and IIP 2013
- Passive microwave and millimeter-wave remote sensing
- NASA GSFC and NGES Space Act Agreement since 2008



NGES

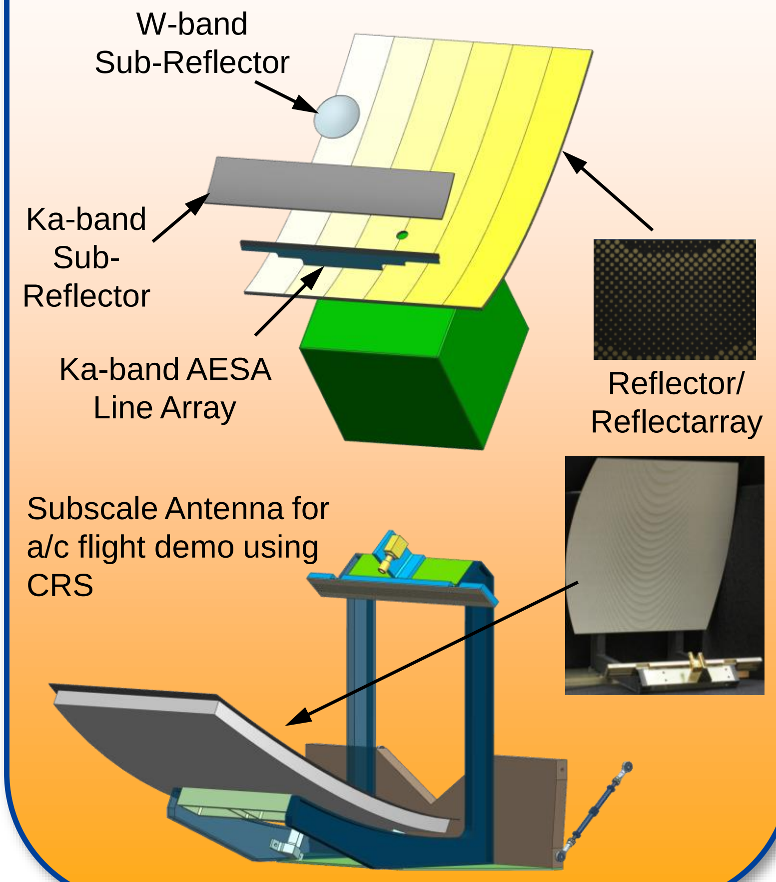
- World leading company for RF electronics and radar system development
- Delivered and flown over 100 space payloads
- Advanced radar technology including Active Electrically Scanning Array (AESA), antenna and back-end electronics



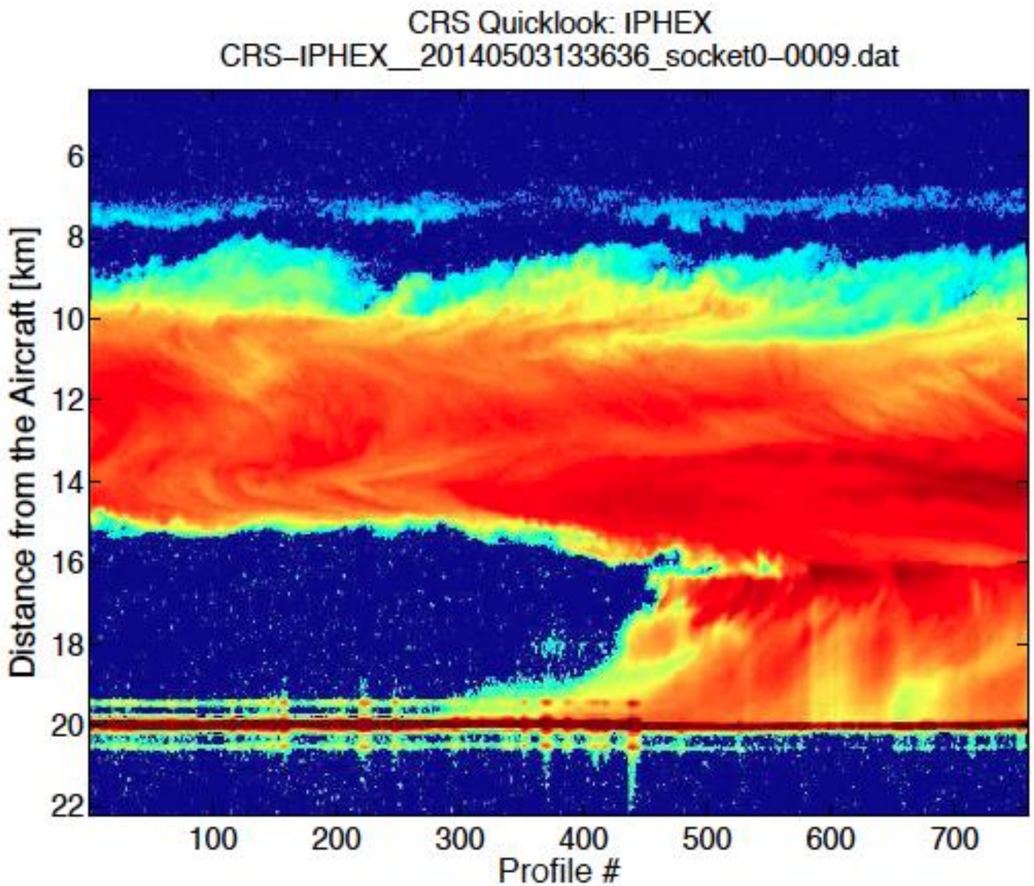
ACE Ka/W-band Dual-frequency Radar Concept (ESTO IIP 2010 project)

- Ka/W-band dual-frequency radar using a single one-dimension curved main reflector
- Ka-band AESA line feed for cross-track scanning
- W-band fixed nadir beam similar to CloudSat configuration
- Innovative reflector/reflectarray technology to achieve focus at W-band and cross-track scan at Ka-band
- Reflector/reflectarray enables co-located beams and reduces the loss due to feed displacement.
- Full scale design of antenna, Ka-band AESA T/R module, and the line feed.
- Designed, fabricated, and tested Ka-band high power amplifier MMIC for the AESA T/R module**.**
- Developed a subscale antenna using the reflector/reflectarray technology and carried out airborne demonstration with W-band CRS

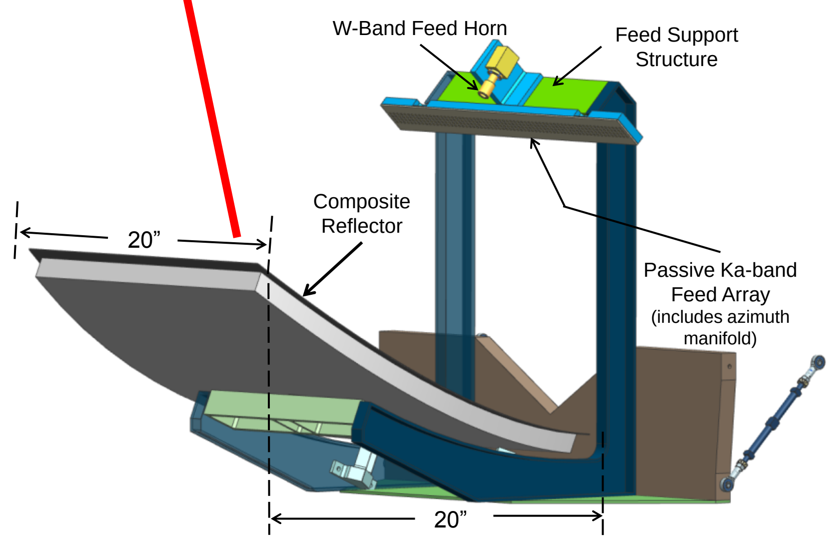
GSFC/NGES ACE Cloud Radar using Reflector/Reflectarray Technology for wide swath Ka-band profiling



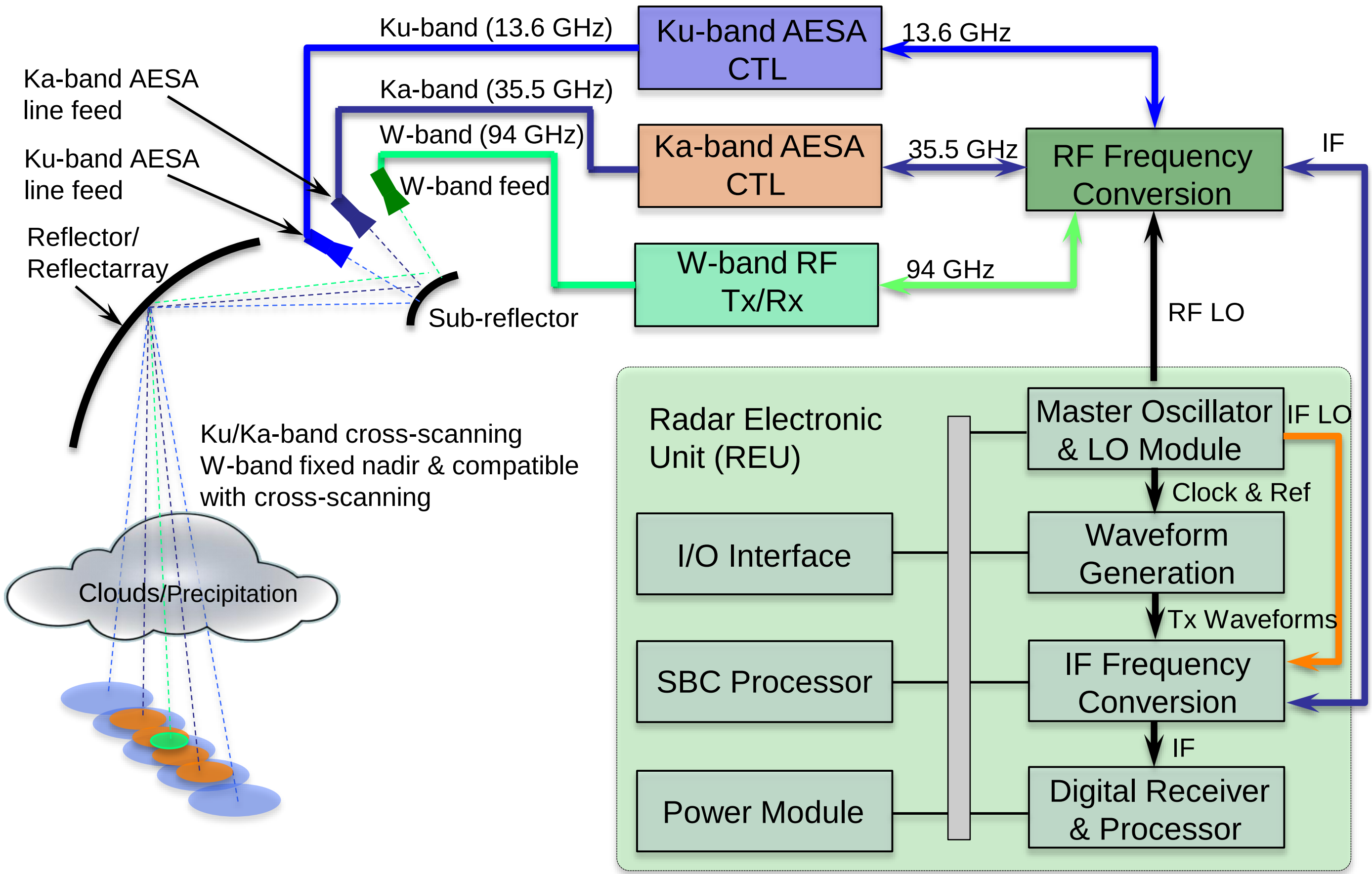
Sub-scale Antenna Demonstration During IPHEX and OLYMPEX Campaigns



Sub-scale antenna in CRS canister in ER-2 tail cone



Tri-frequency Radar Concept for CaPPM (ESTO IIP 2013 project)



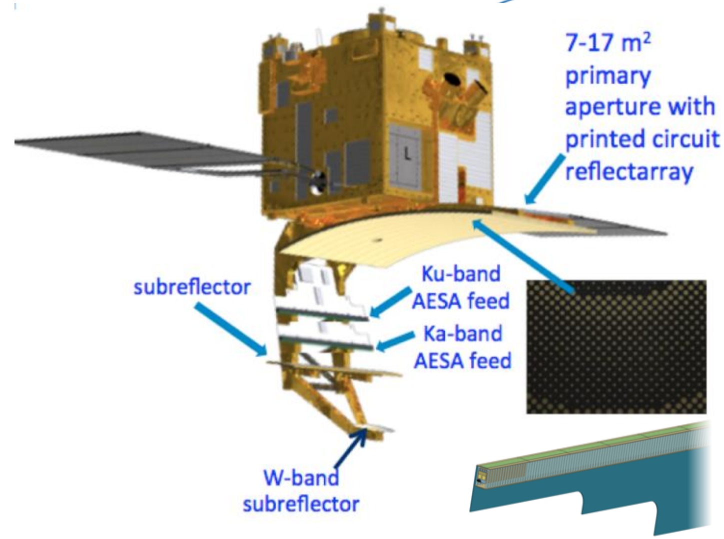
- **IIP 2013 Objectives**
  - Development of a tri-frequency radar concept
  - Tri-band shared aperture antenna study
  - Development of Ka-band Active Electrically Scanned Array (AESA) T/R module
  - Development of radar back-end electronics, including waveform generation module, frequency conversion module and digital receiver/processor
- **ACE Technology Maturation Study (2013)**
  - Performed TRL assessment for Ka/W-band radar
  - Identified key areas to be advanced
  - Defined a pathway to space

Tri-frequency (Ku/Ka/W-band) Radar for Imaging Clouds and Precipitation

Goddard SPACE FLIGHT CENTER NASA NORTHROP GRUMMAN

Discriminating Features

- Shared tri-frequency primary aperture
- Wide swath imaging at Ka-band (>120 km) and Ku-band (>250 km)
- W-band compatible with either fixed beam (similar to CloudSat / EarthCare) or AESA cross-track scanning beams
- Reflectarray enables co-located beams for tri-frequency with optional scanning W-band beam
- Programmable scanning mode
- Leverage high space readiness radar electronics from GSFC and NGES
- Technology Maturation Plan to achieve TRL 6 by 2017/2018



Parameters	CaPPM		
Frequency (GHz)	13.48	35.56	94.05
Orbit Altitude (km)	395-420		
Transmitter	SSPA	SSPA	EIK
Tx Peak Power (W)	2000	2200	1800
Antenna Size (m)	3.0x2.3	3.0x2.3	3.0x2.3
PRF (Hz)	4700	4700	4700
Vertical Res. (m)	250	250	250
Horizontal Res. (km)	5.0x4.0	2.0x1.5	0.75x1.0
Cross Track Swath (km)	250	120	0.75
Nadir MDZ (dBZ)	1.0	-13.2	-33.6
Swath MDZ (dBZ)	4.0	-10.2	N/A
Doppler Vel. Accuracy (m/s)	1.0	0.5	0.2
Polarization Option	Yes	Yes	Yes

Tri-frequency Antenna Trade Study

Rich Trade Space

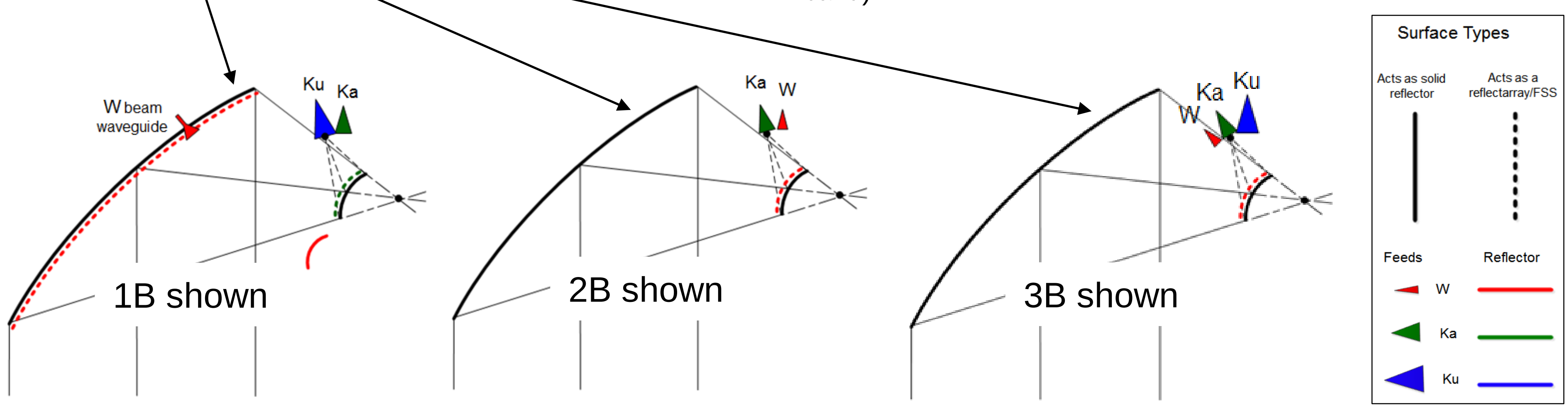
Enables tailoring for particular frequency and/or requirements

	1. Ku & Ka Scanning, W Fixed		2. Ka & W Scanning		3. Ku, Ka, W Scanning					
	1A	1B	2A	2B	3A	3B	3C	3D	3E	3F
	Defocused Ku. Focused Ka. W RA on main.	Focused Ku. Focused Ka via RA on sub. W RA on main.	Defocused Ka. Focused W.	Focused W via RA on sub. Focused Ka.	Defocused Ku & Ka. Focused W.	Defocused Ku. Focused Ka. Focused W via RA on sub.	Focused Ku. Focused Ka & W via RAs on sub & main.	Focused Ku. Focused Ka & W via dual-band RA on sub.	Focused interleave Ku/Ka. Focused W via RA on sub	Separate subs for Ku/Ka & W. RA on both subs.
Tri-Band Capability	Yes	Yes	Ka & W	Ka & W	Yes	Yes	Yes	Yes	Yes	Yes
W-Band Cross Track Scanning?	Fixed	Fixed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Aligned Along Track Beams?	Ka & W	All	None	All	None	Ka & W	All	All	All	All
Matched Cross-Track Beams Possible?	Ku/Ka Only	Ku/Ka Only	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Ku Ka W	Ku Ka W	Ku Ka W	Ku Ka W	Ku Ka W	Ku Ka W	Ku Ka W	Ku Ka W	Ku Ka W	Ku Ka W
2-way Antenna Loss							LPF response of RA does not support 3C	Requires low loss dual-band RA	Qualitative assessment	Qualitative assessment
3-dB Beam Width										
2-way SLL										

RA = reflectarray

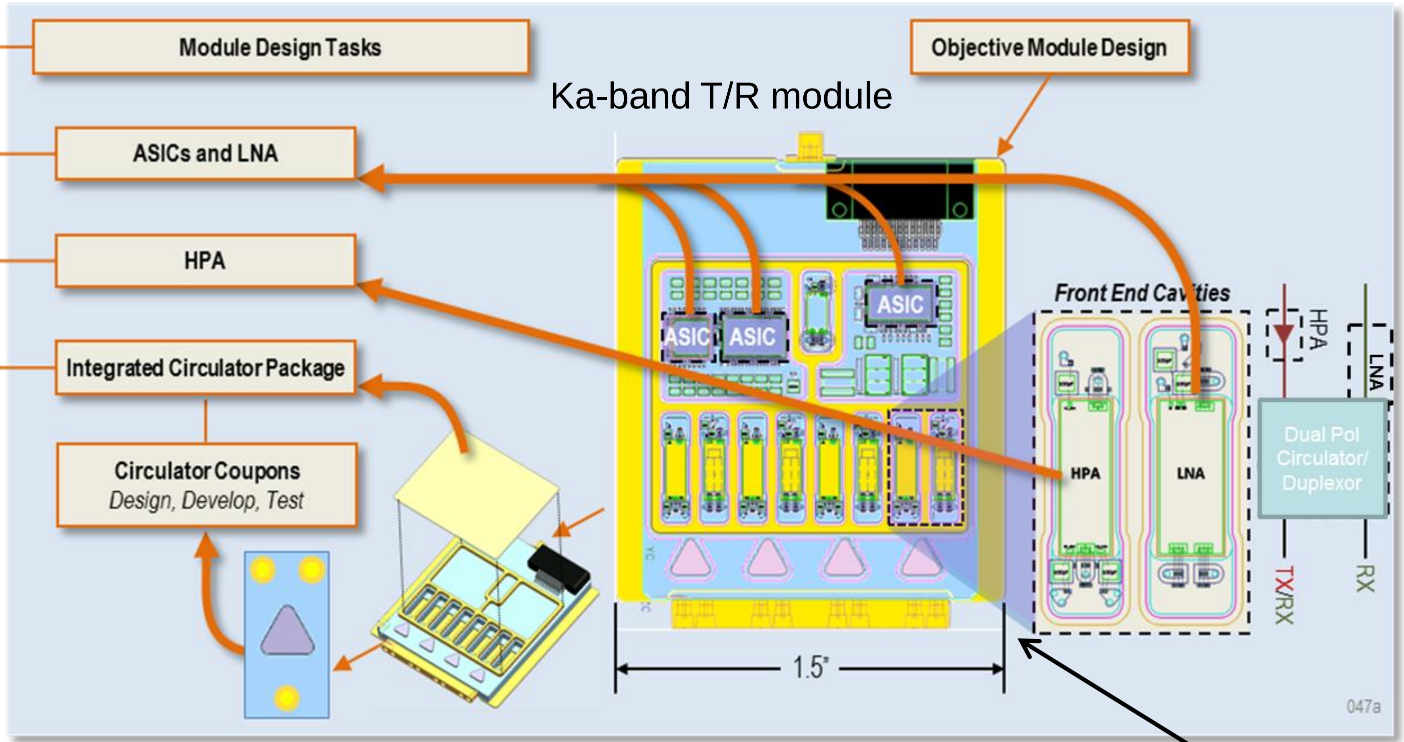
Trade Study Summary

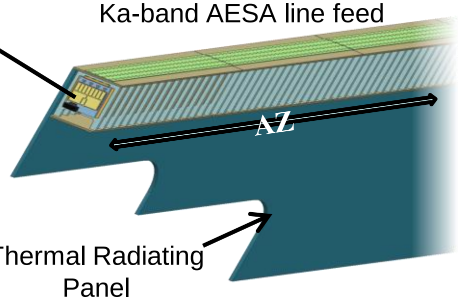
- Identified, assessed 10 candidate architectures (3 classes)
- Down selected primary candidates from each class
- Leveraged IIP 2010 design tools and technologies
  - Reflectarray and reflector design/analysis tools
  - Low loss reflectarray element (including FSS properties)
  - Ka-band AESA and T/R module design
- Evaluated & traded various AESA and T/R module design approaches (Ku, Ka and W-band)
- Explored usage of reflectarrays for tri-freq. architectures
  - Potential benefits in mitigating defocusing scan losses (Ka/W-band)



Ka-Band AESA T/R Module Development

Integrated circulator, MMIC and ASIC development currently under development…





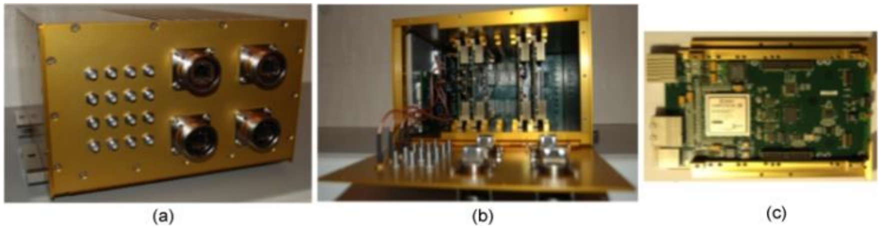
- Held PDR, CDR, FDR for LNA and Key MFC MMIC Circuits
- 3 Design Options For Circulator
- ASIC Requirements for control and telemetry concept

Spaceborne Digital Receiver and Processor

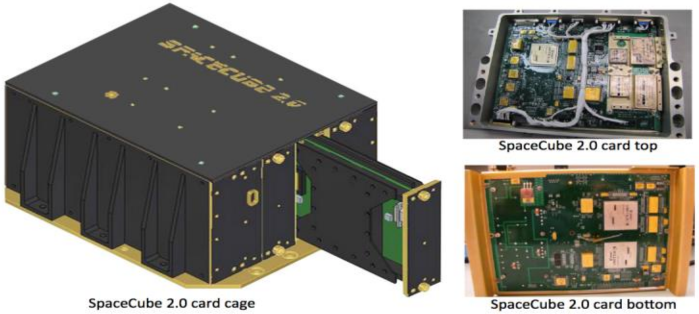
- Hardware and firmware evaluation through airborne Xilinx Virtex-5 based digital receiver and processor

- NASA GSFC SpaceCube 2.0
  - Developed for International Space Station (ISS) and future space mission
  - 3U CPCI architecture
  - Xilinx Virtex-5 FPGA
  - Compact size (7”x5”x8”)

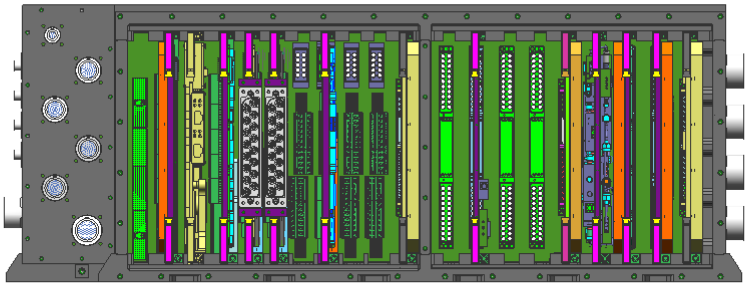
- NGES
  - 6U modules include all radar backend electronic and processor functions
  - Hi-Rel design for space application
  - Xilinx Virtex-5 FPGA
  - TRL 6 by 2017



Airborne digital receiver and processor for hardware and firmware evaluation



NASA GSFC SpaceCube 2.0


NGES Advanced Radar Electronic Unit (REU)

Summary and Path Forward

- Technologies for a dual- or tri-frequency spaceborne cloud and precipitation radar are under development at NASA GSFC and NGES.
- Dual- or tri-frequency, shared-aperture antenna study
  - Evaluated 3 classes and 10 candidate architectures
  - Down selected to primary candidates supporting final mission requirements
  - Addresses various band combinations with options for W-band fixed beam and scanning
  - Includes application of proven reflectarray technologies
- Ka-band AESA T/R module development
  - Module RF and mechanical design
  - MMIC and circulator development approaching fab
  - GaN HPA MMIC design verification test underway
- W-band compatible with either fixed nadir beam or AESA scanning beam
  - Leverage high TRL CloudSat technologies
  - Compatible with AESA cross-track scanning design
- Ku-band AESA technology is mature
- Continue to enhance the Technology Readiness Level (TRL) for space


NASA
NORTHROP GRUMMAN
ACE/CaPPM
EarthCare
GPM
CloudSat
TRMM
Thank You!
Developing technologies for the next
generation spaceborne atmospheric radars